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On the Geodetic Stability of the Goddard Optical Research Facility

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ABSTRACT

Seismic observations of earthquakes and blasts, geologic analysis of Landsat images, and a search of the historical record all contain no evidence for tectonic motion at the Goddard Optical Research Facility. Some faulting is present in the area but no evidence of seismic activity was found. No elastic resonances in the range from 0.3 to 15 Hz were found. It is concluded that, except for ground water induced changes, the facility is presently stable at least to the 0.5 cm level.

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HISTORY AND EMPLOYMENT OF THE GODDARD OPTICAL RESEARCH FACILITY SITE

The technique of laser ranging between ground stations and earth orbiting satellites was developed at the Goddard Optical Research Facility (GORF) site because of NASA's requirements for precise determination of spacecraft orbits. The technique determines the distance (range) to a spacecraft by measuring the round-trip travel time of a pulse of light from a laser source to a spacecraft retro-reflector array. Natural applications of these measurements include accurate determinations of the earth's gravity field and locations of the ground stations.

From its inception, the focal point of this technique has been at the GORF site, located several miles northeast of the Goddard Space Flight Center. Operations were initiated with the delivery of a suitable ruby laser in 1962. In 1963 a Nike-Ajax radar pointing system was modified to accommodate the laser. This system, the prototype for later mobile laser systems (MOBLAS), tracked the satellite Beacon Explorer-2 beginning in October 1964.

In 1972, the multimode astronomical telescope at the GORF site was converted to the Stationary Laser Facility (STALAS) to support the San Andreas Fault Experiment (SAFE). While the primary objective of SAFE was to determine baseline length changes between the North American and Pacific plates, accurate trans-U.S. baseline distances were also obtained between STALAS and west coast sites.

Until recently, the GORF site contained the fixed STALAS system and neighboring monumented concrete slabs or foundations used for development, check out and validation of various mobile laser ranging systems. In early 1981 the STALAS instrument was deactivated and the primary ranging duties at GORF were assumed by MOBLAS 7.

The objective of the Crustal Dynamics Project, established at Goddard in 1980, is to employ satellite laser ranging (SLR) and Very Long Baseline Interferometry (VLBI) techniques to measure accurately rates of crustal motions. Previous existing NASA geodynamic projects such as SAFE and the Pacific Plate Motion Experiment were incorporated into the Crustal Dynamics Project, resulting in the project being the focal point for all NASA geodetic and geodynamic investigations. The scientific objectives of this project include studies of plate tectonic motions and deformation and strain

accumulation at plate boundaries and within plates. The GORF site is a key, permanently occupied base station for the more than 50 continental U.S. sites planned for repeated occupancies during the six-year lifetime of the Project. Understanding of large scale crustal motions requires that either the observing stations be located at stable locations with no significant localized surface motions or that the extent of these motions be measurable and understood. At present, it is assumed that the eastern U.S. stations, like GORF, are stable, and that changes in baseline lengths between these stations and other sites reflect changes within the more active regions. It is, therefore, important to verify this assumption for the GORF site.

REGIONAL GEOLOGY

The GORF is located on the Maryland coastal plain, about 12 km east of the boundary (the fall line) between the coastal plain and the piedmont province to the west (Figure 1). The coastal plain, as described by Murray (1961) is actually a coastal geosyncline: a wedge of sediments dipping gently and thickening toward the continental margin to the southeast. The continental shelf is geologically continuous with the coastal plain. Coastal plain sediments thicken from zero at the fall line to several thousand feet at the coast. At the GORF site, they are underlain at a depth of about 150 meters by crystalline rocks similar to those exposed in the Piedmont. It will therefore be convenient to summarize the site geology under two headings: coastal plain and adjacent piedmont.

Coastal Plain

The site is in the Chesapeake-Delaware Embayment of the Atlantic Coastal Plain (Murray, 1961), a tectonic downwarp named for the two large drowned river systems, Chesapeake Bay and Delaware Bay. Rocks of the Atlantic Coastal Plain in general consist of upper Mesozoic and Cenozoic sediments deposited under near-shore marine or fluvial conditions, chiefly sands, clays, marls, and gravels. The GORF is on one of the oldest and stratigraphically lowest of the Coastal Plain units, the Cretaceous Patapsco Formation and Arundel Clay (using the nomenclature of Johnston, 1964, and Cooke and Cloos, 1951). This general unit is described by Johnston as consisting of "dark-gray massive clay containing lignitized wood and saurian bones; overlain by massive maroon clay and

varicolored sand and clay." Sediments exposed at the site are chiefly maroon clay overlain by a few feet of unconsolidated sand, both white and brown, characterized by subangular grains. Lenses and layers of limonite-cemented sand are common. The Patapsco Formation and Arundel Clay are underlain, at a depth of around a hundred meters, by the Lower Cretaceous Patuxent Formation, consisting of sand, large pebbles, and clay. The Patuxent Formation, locally the lowest Coastal Plain unit, unconformably overlies crystalline rocks continuous with those of the Piedmont, which will be described separately.

The geologic structure at the site, except for possible fractures, which will be discussed separately, is simple. The Coastal Plain sediments dip very gently to the southeast. The actual dip is about one degree; for engineering purposes the sediments at the site can be considered locally flat-lying.

Piedmont

The piedmont province in this area is physiographically a low plateau, which can be considered a peneplain since it was formed by erosional truncation of steeply-dipping rocks of variable lithology. It is part of the Appalachian orogenic belt, and consists in part of a complexly-deformed series of early Paleozoic metasediments, the Glenarm Series (Cleaves et al., 1968), intruded by granitic and gabbroic rocks. These Paleozoic rocks in the Baltimore-Washington area overlie a Precambrian basement of Grenville age, which diapirically intrudes the Paleozoic rocks to form the well-known Baltimore gneiss domes (Figure 1).

The nature of the crystalline basement under the site is not known directly. However, wells to basement just west and northeast of the site encountered "granite" or "gneiss" (Drake et al., 1956; Hansen, 1968). Drillers' lithologic descriptions tend to be very general, but it seems safe to assume that these terms refer to a light-colored crystalline rock as opposed to the much darker Baltimore gabbro. The most likely possibilities are one of the Paleozoic granitic intrusives, a gneissic member of the Glenarm Series, or, more likely, the Baltimore gneiss (Hopson, 1964).

The structure of the Piedmont can hardly be described briefly. In the area just west of the laser site, the regional structure is dominated by northeast-trending tight folds (Figure 1). Both

synorogenic granite intrusions and the diapiric Baltimore gneiss domes tend to follow this trend. The Baltimore gabbro north of Baltimore also trends northeast in outcrop, perhaps as a result of tectonic emplacement along faults with this direction (Crowley, 1976). The gneiss domes and Glenarm structures just west of the Fall Line follow a broad upwarp termed the "Baltimore anticlinorium" by Cloos (1964). The site may overlie the extreme east limb of this structure.

POSSIBLE FAULTS IN THE SITE REGION

A knowledge of active or potentially active faults at or near the GORF is obviously important to estimating tectonic stability. The unconsolidated nature of the Patapsco Formation, and other Coastal Plain sediments coupled with low relief and vegetative cover, make it difficult to locate faults. Consequently, the following is largely an inferential estimate drawn from several data sources.

First, it should be pointed out that recent COCORP reflection profiling indicates that much of the eastern Piedmont and Coastal Plain may be underlain by major thrust faults extending possibly to the continental margin (Cook et al., 1979; Harris and Bayer, 1979). If this is true, the site is on a large thrust plate. However, the supposed faults probably date from the early Paleozoic, and are thus not likely to be active now. Of more direct importance are two faults detected by active sounding about 35 km south of the site in the Danville-Cheltenham area (Jacobeen, 1972). Although not visible on Landsat imagery, they are shown on Figure 1.

York and Oliver (1976) have summarized the evidence for Cenozoic and Cretaceous faulting in the east. Of particular interest here is their summary of literature reports of faulting observed in Upper Marlboro, MD and within the confines of Washington, DC. In each case where the type of faulting could be determined (3 out of 4), the faults were reverse faults with a meter or more of displacement. The deep faults reported by Jacobeen (1972) from active seismic sounding have some 76 meters displacement at depth. Jacobeen interpreted these faults as east-dipping reverse faults.

Photolineaments have been widely used to map possible faults in Coastal Plain sediments; examples are given by Murray (1961). Withington (1973) was the first to use Landsat images to map lineaments in the Maryland Coastal Plain; however, he was forced to use the first Landsat image

of the area, which was not of good quality. Accordingly, a later, low sun-angle picture was used to search for additional lineaments (Figure 1). A number of these were apparent; one, the lower Patuxent River, had been mapped as a lineament by Withington. However, it is evident on the Landsat image that three upper tributaries of the Patuxent exhibit remarkably straight and parallel courses. These lineaments cut across the outcrop trend at a substantial angle, and hence are not controlled by stratigraphy. A few other parallel lineaments nearby and on the Eastern Shore are also visible, and the straight stretch of the Potomac River just south of Washington may also be considered a lineament since it does not follow the fall line. It is suggested that this family of lineaments be further investigated, although there is no reason to think they are currently active even if they are indeed faults.

A few southeast-trending transverse lineaments in the Piedmont have also been mapped. It should be pointed out that the northwest trends of the Potomac, Susquehanna (at Havre de Grace), and Delaware (at Trenton) Rivers have also been proposed as megalineaments by Hobbs in 1904 (Murray, 1961).

The southernmost of the Baltimore gneiss domes is shown by Cleaves et al. (1968) as fault-bounded, as are parts of the Baltimore gabbro, and there are probably other northeast-trending faults not recognized because they parallel regional foliation trends.

A field examination of the area of the MOBLAS 7 pad at the GORF was conducted to check for slump features or other evidence of tectonic motion. In addition, the regions northwest and immediately east of the GORF were surveyed for outcrops and faults during the siting of the Ellicott City, MD (ECM) seismic station. The regions covered by these examinations correspond to a circle 2 km in diameter centered on the GORF, a rectangle 2 km wide and 3 km long proceeding east from the GORF, and a segment of a circle 20 km in radius bounded by due north and due west.

No evidence of slumping or faulting was found at the GORF. The MOBLAS 7 pad is located on a small hill covered by grass. Thus, although no evidence of ground disturbance could be found, the depth of the sod could mask as much as 0.5 cm of slumping. This is the largest permitted motion at the pad. Good ground exposures were found within 100 meters of the pad. None of these exposures yielded any evidence of ground disturbances.

The survey area east of the GORF included the lineaments shown in Figure 1a. As in previous studies (Webster et al., 1979), the surface expression of the lineaments is subtle in the extreme. The lineaments are very shallow depressions with no evidence of slumping or ground cracks. This is similar to the structures observed by Jacobeen (1972) over the deep faults. Jacobeen felt that the surface lineaments were zones of differential compaction and not related to the faults since the faults offset only the deepest strata. Differential compaction is a good explanation for our area since the packing of the lineament surface seems tighter than the surrounding area.

The survey area northwest of the GORF spans the fall line and includes the southern portion of the Woodstock gneiss dome (WD in Figure 1a). We found no evidence of surface faulting in the area southeast of the gneiss domes. According to Cloos (1964), the only faults in this area are associated with the domes. In particular, the dome on which ECM is located is fault-bounded on its southernmost limb. The expression of these faults is subtle and is obscured by ground cover. We did not find any evidence of recent motion on any of these bounding faults.

In summary, there are several photolineaments near the GORF that deserve further study. However, there is no clear geologic evidence (fault scarps, stream offsets, etc.) that these or any other nearby Coastal Plain faults are now active.

LOCAL AND REGIONAL SEISMICITY

Although the GORF is in what is conventionally thought of as an active region, frequent small ($m_b \sim 2.0$) earthquakes occur within 500 km of the site. Bollinger (1973) has identified active areas in southwestern Virginia and central Virginia which are each responsible for 3 to 6 events per year. Aggarwal and Sykes (1978) have shown that the Ramapo fault in New Jersey has been responsible for perhaps 33 events, in the range $1.0 \leq m_b \leq 3.3$ from 1962 to 1977. Further, the Lancaster, PA area has experienced roughly 4 events per year with $m_b \leq 3.5$.

To illustrate the level of seismicity, Figure 2 gives the hypocenter map for Maryland, Delaware, West Virginia and Virginia and parts of Pennsylvania and New Jersey for the period 1977–1980. All events reported by the Pennsylvania State University network, the Southeast Regional network or

observed by Goddard seismic stations are included with no lower cutoff in body wave magnitude. In Sykes' (1978) view, these levels of activity are the manifestation of the interaction between oceanic fracture zones and the continental crust. Sykes' hypothesis presents a useful mechanism for concentrating stress in the regions where the fracture zones intersect zones of weakness in the continental crust. Although it is not always possible to trace the surface-expression of the fracture zones in the region covered by Figure 2 (Lowman et al., 1980), the spotty distribution of seismicity lends credance to the hypothesis.

Taken together with the recent COCORP results showing extensive thrusting in the east (Cook et al., 1979), Sykes' work suggests that some form of block tectonics on a regional scale may be the principal tectonics in at least the middle part of the east. Although the distribution of seismicity suggests that the GORF is not near any of the block boundaries, there is evidence of recent faulting in the region. The shallow depth of all reported hypocenters indicates that the upper thrust plate is the one containing the blocks.

Since very few earthquakes have ever been reported within 50 km of GORF, significant seismic activity on the reported faults is not occurring now. In five years of operation of ECM, only one suspicious event was observed 12 km northwest of GORF. However, this event has been identified with a rockfall (see Appendix 1). The historical record (Bollinger, 1969) contains 11 shocks in this area from 1758 to 1968. Most of these were in the Baltimore area with a few (3) reported in the Annapolis region. All, however, are pre-instrumental locations.

LOCAL CRUSTAL STRUCTURE

During the initial construction of GSFC, a deep water well was drilled on the GSFC main property. Although the well is about 4 km southwest of the GORF, the lithologic characteristics are expected to be typical of the region. According to Hansen (1968), the well "reached a depth of 455 ft. and the dominant lithology was clay with thin layers of sand." Although this well did not reach basement, basement depths from surrounding wells, especially one at Glenn Dale, MD (2 km east of GSFC), shows that bedrock would have been reached at 152 m. The rock type observed in the Glenn Dale was "Gneiss."

In the subsequent analysis, the adopted velocity model is derived from this well control. Velocities from Press (1966) were used. A two-layer model with 152 m of clay top cover and a gneissic layer to the Moho at 30 km were assumed initially. A series of large blasts (50 kiloton) at the Pennsylvania Glass and Sand Company (north of Hagerstown, MD) were observed to refine the model. Observations of these blasts were taken by the PSU network (Angelone, personal communication), and by Goddard fixed stations at Green Bank, W VA (GBV) (Webster et al., 1980) and Ellicott City, MD (ECM). Temporary observations were made from Boyds, MD (NAS1) and from a low gain station in a gravimeter pit near the laser telescope at GORF (NAS2). Table 1 gives instrumental characteristics and locations for the stations used in this analysis. The primary refinement was a direct determination of the depth to the Moho for each station.

Allenby (1980) reported a Moho depth of 32 km in the region around GSFC. The blasts (at 78°12′, 39°40′) were far enough from the GORF for P_n to be well observed. The clearest recordings of the Moho phases were at ECM and NAS2. The recording at GBV was of lesser quality due to distance while that at NAS1 had lower amplitude than the fixed stations. Although the seismometer at NAS1 was in direct contact with the Triassic diabase, the amplitude was only half the value at NAS2 (scaled for the difference in gain). The inferred Moho depths given in Table 2 are consistent with the analysis reported by Allenby (1980). It is of interest to note that these results do confirm the deepening of the Moho to the west.

In Figure 3, we give the final velocity column under the GORF which results from the analysis above. For comparison, the velocity column under ECM is also given. Recent work suggests that the Conrad discontinuity represents a significant change in crustal structure. We were not able to observe Conrad phases at any of our sites since the closest station was 110 km from the source.

To investigate the potential for motion of the sediments under GORF, we compared the first arrival amplitudes for earthquakes observed at ECM and GORF. According to Bycroft (1978), the relative importance of soil/structure interactions can be derived from this kind of study. This analysis is of importance because of the possibility that resonance vibrations of frequency less than 15 Hz could contribute to the error budget of the laser ranging residuals. Due to the wedge shape of the

Table 1
Instrument Configuration

Station Location	ID	Latitude	Longitude	Altitude (Meter)	Seismometer Type	Gain (10^4)	Surface Type	Notes
State College, PA	SCP	40°47.7N	77°51.9W	352	SPZ	4	Limestone	Via PSU Net
Ellicott City, MD	ECM	39°15.8N	76°15.8W	140.2	SPZ	7	Gneiss	
Green Bank, W VA	GBV	38°25.8N	79°50.7W	801.5	SPZ	7	Stream Bed Deposits	
Boyds, MD	NAS1	39°10.0N	77°21.0W	200	SPH	1	Diabase	Temporary Site
Beltsville, MD	NAS2	39°01.2N	76°49.6W	130	SPH	0.5	Clay	GORF Site

Table 2
Observed Moho Depths

Station ID	Distance from Shots (km)	Moho Depth (km)
SCP	125	-
ECM	120	33
GBV	200	48
NAS1	110	36
NAS2	128	33

coastal plain sediments and the hardness of the crystalline basement, vibration theory suggested the possibility of low frequency resonances strong enough (perhaps 1 cm at peaks for the observed velocity distribution) to influence the range residuals. See Sommerfield, 1950, chapter 8, section 45, for a discussion of the elementary elasticity theory of this problem.

Events within 2,000 km which were observed at both stations were used in this analysis. Bycroft's amplification constant a_o for a flat plate model was determined by a least squares fit of the observed amplitude ratios to the functional form of the amplitude:

$$R(\omega) = \left\{1 + a_o^2(\omega)\right\}^{-1/2}$$

This differs from Bycroft's (1978) original form in that we have allowed for a possibility that there is a frequency (and thereby distance) by treating a_o as a Taylor series in ω dependence. In addition to this analysis, ray tracing techniques (Bullen, 1976) were to calculate the arrival angles for each event at the GORF site. Although the range of arrival angles is not large, it was thought that it might be possible to measure the influence of path length on the attenuation. A total of 12 events with distances ranging from 120 to 2,000 km were used in this analysis. In the far distance range, Caribbean, western Mexican, and Californian events were observed. In the near distance, events in Pennsylvania, New Jersey, Virginia, and West Virginia were observed. Obviously, the azimuth coverage for the near anf far zones is not the same. Since further data is being gathered, the conclusions reported here should be regarded as preliminary in detail.

No correlation with azimuth, characteristic frequency, or magnitude was found. A small correlation with nadir angle was found indicating that the sedimentary path length is a significant factor in the amplitude ratio. For near normal incidence, $a_0 = 0.49$ ($R = 0.90$) while for 45° incidence angle, $a_0 = 0.95$ ($R = 0.72$). Thus, there is no evidence for resonance amplification below 15 Hz regardless of angle. However, due to the sensitivity of the seismometers and recorders, only the very strongest resonances below 0.3 Hz would be detectable. A maximum amplitude less than 300 microns was observed for the strongest signals in the low frequency band.

The observations at GORF indicate the frequencies above 15 Hz are little attenuated. Railroad traffic as far away as Laurel, MD can be detected with an amplitude of three times the background noise. The characteristic frequency of the nearer signals is 20–30 Hz. Although we saw no evidence of high frequency resonances in our data, large signal amplitudes (300 microns) and long signal durations (from 5 minutes to 30 minutes) were observed for freight trains on the nearest (10 km) lines.

CONCLUSIONS

Although there is evidence for recent faulting, and therefore potential seismicity, in the vicinity of GORF, we found no crustal seismicity within 30 km of the site.

No low or high frequency resonances were detected. With our instrumentation, this conclusion applies to the band $0.3 \leq f \leq 30$ Hz. We did find evidence for a relatively low attenuation for frequencies above 15 Hz. We do not expect that the high frequency signals will contribute to the range residuals unless the precision of the measurements is substantially better than the 0.3 cm assumed for typical satellite laser range residuals.

We found no strong evidence of tectonic motion in the vicinity of the GORF. The historical record (Bollinger, 1973; Coffman and von Hake, 1973) contains a few earthquakes in the Washington, Baltimore, Annapolis region. All of these events are pre-instrumental (mostly pre-1900). It is possible that the epicenters were near the GORF but recent seismic history suggests that is not very likely.

We conclude that, except perhaps for elevation changes due to ground water, the GORF is stable to at least the 0.5 cm level. The site is, in any case, tectonically quiet at present.

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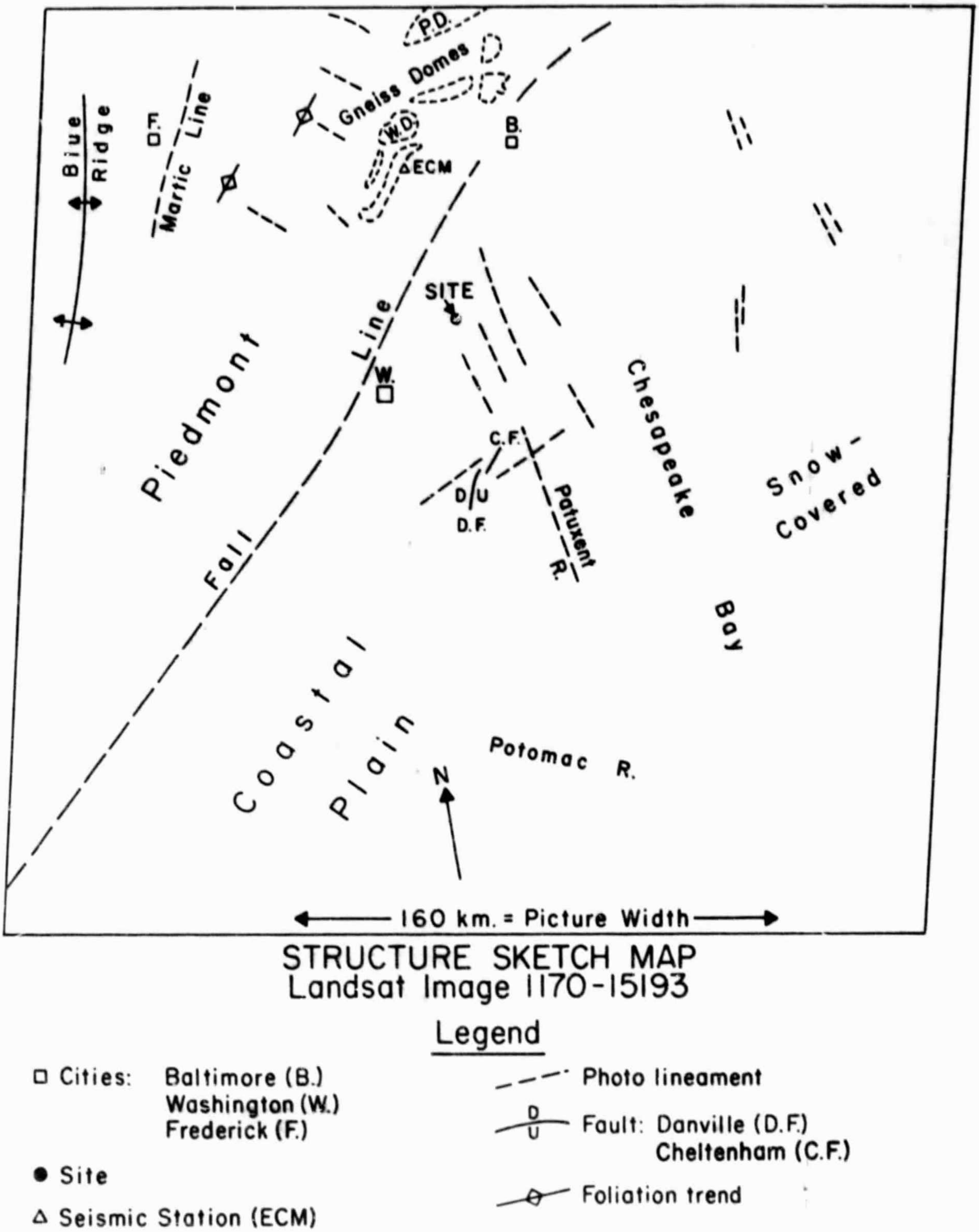

Figure 1a. Structural Sketch Map of the Goddard Optical Research Facility Region. Landsat Image 1170-15193 is the Map Base.

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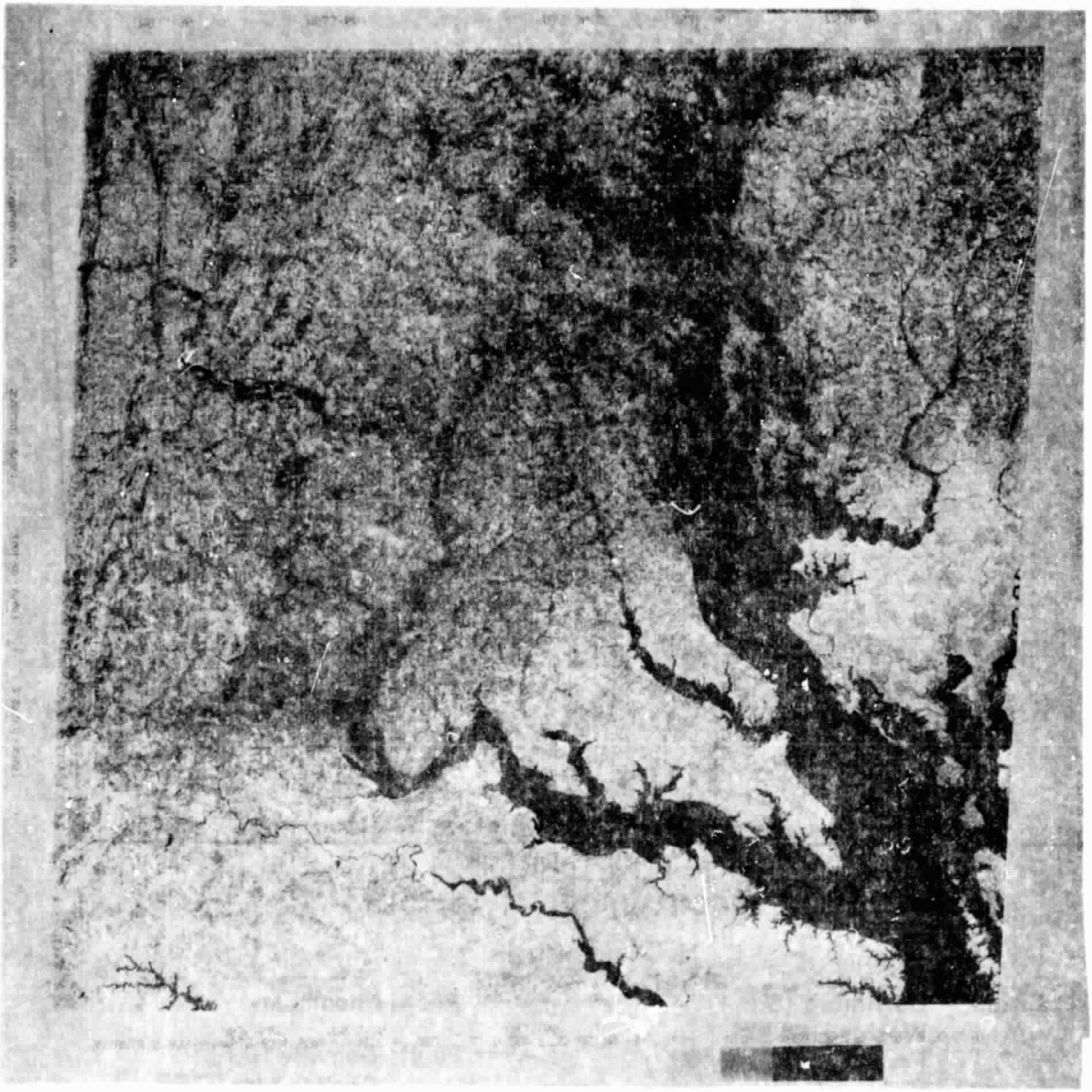
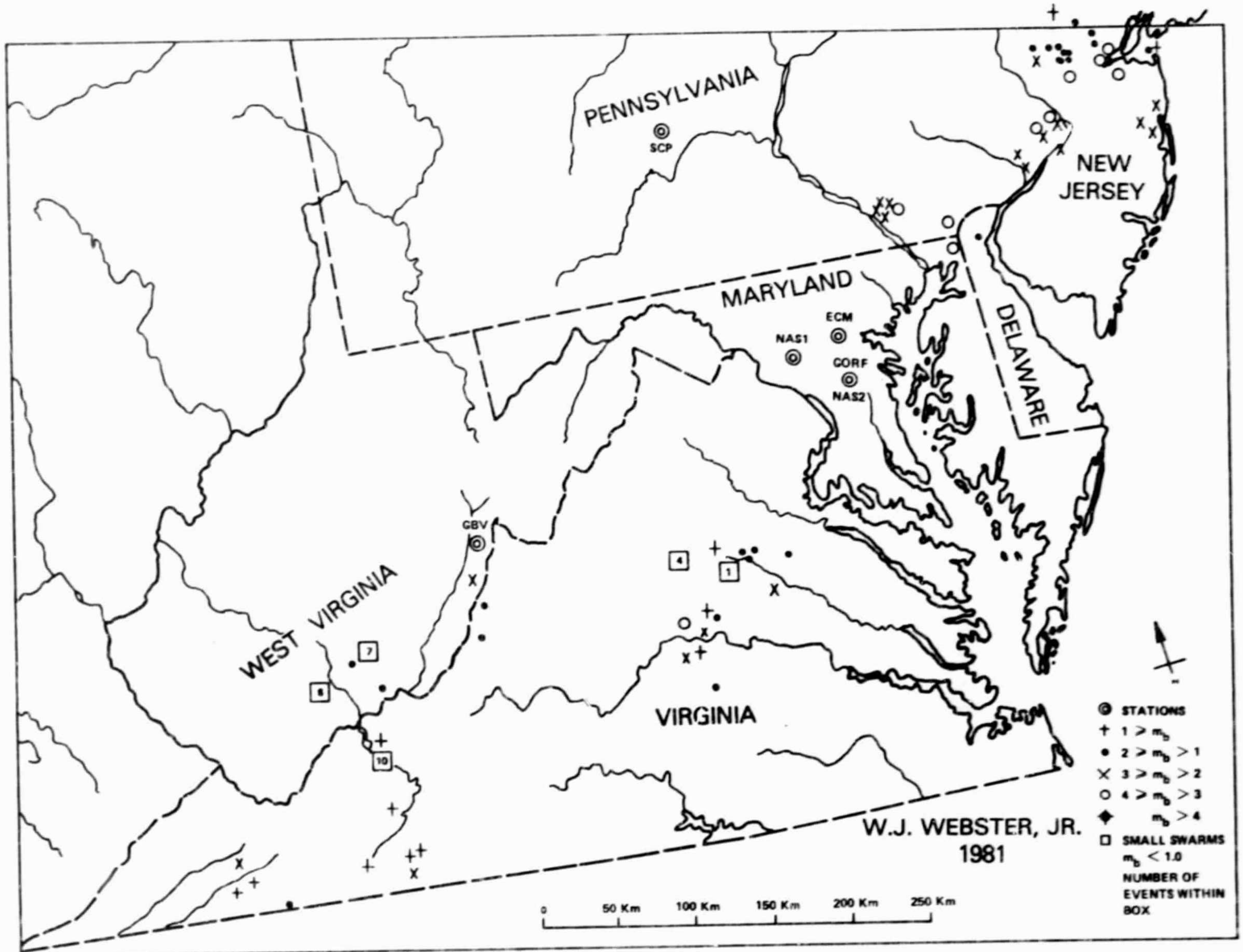


Figure 1b. Landsat Image 1170-15193



SEISMICITY OF THE MID-ATLANTIC REGION JANUARY 1, 1977 - DECEMBER 31, 1980

Figure 2. Hypocenter Map for the States of Delaware, Maryland, West Virginia, Virginia, and Parts of Pennsylvania and New Jersey Covering 1977–1980. ECM, SCP, GBV, NAS1 and NAS2 are the Seismic Stations Referred to in the Text. See Table 1.

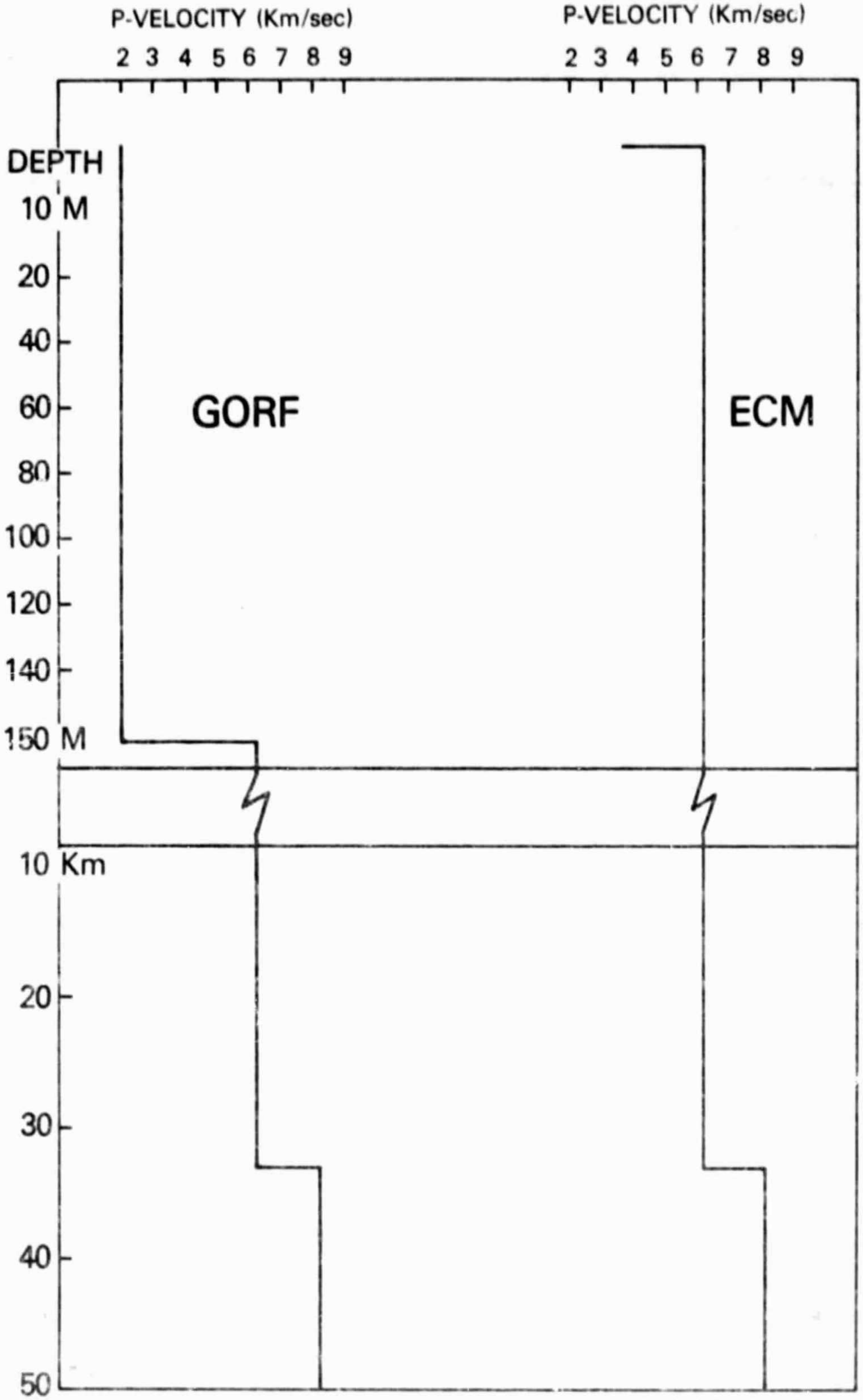


Figure 3. Observed Velocity Column under the Ellicott City Seismic Station (ECM) and the Goddard Optical Research Facility (NAS2).

APPENDIX 1

A LOCAL EARTHQUAKE NEAR ELLICOTT CITY POSSIBLY DUE TO A ROCK FALL

The record of 3/12–13/80 for our Ellicott City seismic station (a portion is given in Figure A1) showed what appeared to be a quarry blast at 03:47:21:3 GMT on 3/13/80. Since there is a regulation in Maryland which forbids blasting after sunset, this event was unusual. Further examination showed the following peculiarities:

a. P-S = 1.1 sec, most quarries are over 5 sec P-S away. Only one is between 3 and 5 seconds.

b. The total duration (from first motion until the signal level is the same as the noise level) is 25% greater than for daytime blasts.

c. While the overall wave shape is similar to the blasts, the peak S amplitude and the coda decrement are noticeably different.

All these factors suggest something strange.

Fortunately, the experimental set-up in the gravimeter pit at the Optical Facility was running. Interestingly enough, the event also shows up on the record from the gravimeter pit. A two-station epicenter solution was done using the velocity model discussed in the text. Two potential epicenters result from the analysis and are shown on a geographic contour map in Figure A2. The circles around the locations correspond to 0.1 sec timing errors for each station.

A priori, there was no reason to prefer one location over another. No known surface faults are in either area although both locations are near the hinge line. A body wave magnitude of 0.9 was calculated for the ECM record. Clearly whatever the event was, it had relatively low energy. It should also be noted that ECM magnitudes tend to be about 0.2 higher than Blacksburg estimates for the same event. The true magnitude may actually be only 0.7.

The evening weather was relatively warm and damp, followed by a temperature fall to below freezing and snow. The previous day had been cold and cloudy. A survey of the USGS quadrangle maps showed no active quarries or mines near either hypocenter.

There is, however, an inactive quarry at Hollofield, MD (the northern most possibility). According to Martha Jarosewich, a fresh rock fall was present when she re-examined the quary on 3/15/80. The size of the rock fall she reported (about 20 cubic meters) is roughly consistent with our magnitude ≤ 0.9 event. As a test, the location of the event was fixed at the quarry and the residuals computed. For both NAS2 and ECM, the residuals are less than the timing error.

Figure A1

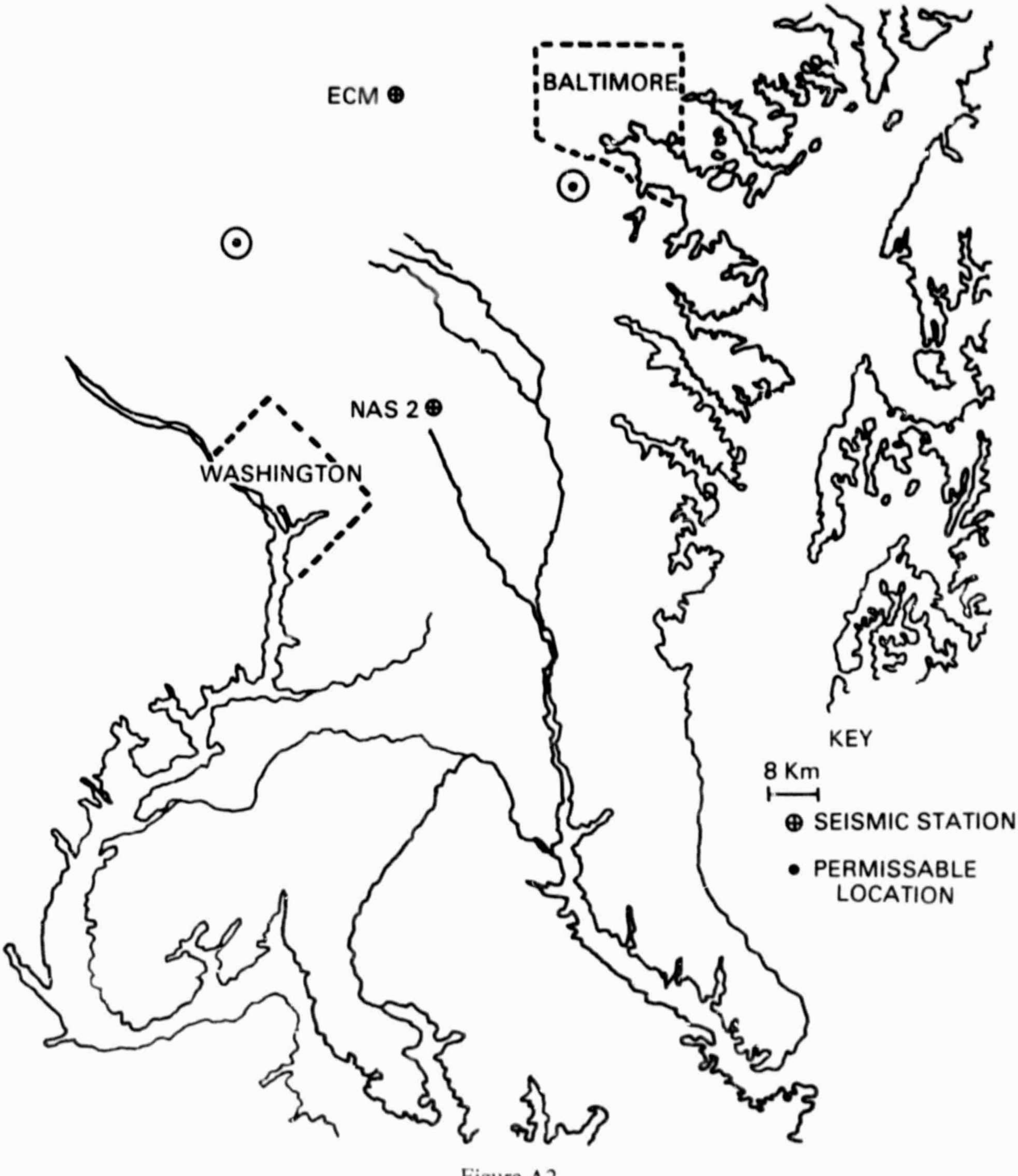

BALTIMORE
ECM
NAS 2
WASHINGTON
KEY
8 Km
SEISMIC STATION
PERMISSABLE
LOCATION

Figure A2